Workshop at Griffith University
Fundamental Soil Mechanics Principles (Part 2)

Groundwater, permeability and unsaturated flow

Effective stress / soil shear strength are functions of the total stress and pore water pressure. Pore water pressure often represents a large proportion of loading on retaining structures.

Most problems in slope engineering are associated with groundwater, especially hillslope groundwater conditions.

This section will cover the following aspects:

1. Steady state groundwater flow and the calculation of associated pore water pressures and flow rate.

2. Transient infiltration of rainwater in unsaturated ground - wetting front approach.

Appreciate the effect of subsurface drainage, surface protection on slope stability and a basic conceptual model on hillslope hydrogeology.

The Terms:

Groundwater table -	The level at which the gauge pore water pressure is zero (also called phreatic surface).
Aquifer -	A permeable water-bearing stratum that transmits water.
Pore water pressure -	(Gauge pore water pressure) the pressure of pore water measured relative to atmospheric pressure.
Standpipe piezometer -	A standpipe piezometer is essentially a small-bore pipe with a porous tip, which is installed in the ground in order to measure the pore water pressure at a particular point. After installation, the water level in the piezometer moves up or down until the column of water in the standpipe is the same as the pore water pressure in the ground just outside the tip. Due to the volume of water must flow into or out of the standpipe before pressure equilibrium is reached, the response of standpipe piezometer can be slow for less permeable ground. Other types of piezometers (i.e. pneumatic, hydraulic and vibrating wire), which involve much smaller amount of water in the measuring device, can be used. The maximum groundwater level in a standpipe piezometer can be measured by a string of small buckets (Halcrow buckets).

Piezometric level - Level of groundwater pressure indicated by piezometer.

Perched water table - A localized water table exists above the main groundwater table where a local reduction in basal permeability occurs in conjunction with recharge from above or drainage from below. Perched water table may be transient, developing rapidly in response to heavy rainfall and dissipating equally quickly, or more permanent, responding to seasonal variations in rainfall level.

Groundwater flow in saturated soil

Groundwater through the soil pores is driven by a hydraulic gradient, i, which is defined as the (negative of the) rate of change of total head with distance

Hydraulic (total) head = Pressure head + Elevation head

The ease with which groundwater can flow through the soil pores is quantified by the soil permeability, k. Roughly, k is proportional to the D_{10} size of the soil.

In most cases, the volumetric flowrate of water q through a soil element of cross-sectional area A is given by Darcy's Law:

$$q = A\ k\ i$$

Measurement of permeability of soil through laboratory and field testing has been covered in HC course, please refers to standard text book if needed.

Mathematics of groundwater flow

Governing equations are derived based on inflow and outflow through a soil element. For steady state condition, inflow = outflow for each element of soil. Applying Darcy's Law to the three independent directions:

$$k_x\ \partial^2 h/\partial x^2 + k_y\ \partial^2 h/\partial y^2 + k_z\ \partial^2 h/\partial z^2 = 0$$

For isotropic soil, $k_x = k_y = k_z$, the equation is simplified to Laplace's Equation :

$$\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2 + \partial^2 h/\partial z^2 = 0$$

Plane flow and Flownet

Many geotechnical structures are long in comparison with other dimensions. There is only significant flow in the plane of the cross-section. The problem is reduced to two dimensions, in which the Laplace's Equation can be solved graphically.

A flownet is a network of flowlines, which represent the path of individual fluid particles, and equipotentials along which the total head is constant and therefore no flow. The use of flownet :

1. to provide a graphical representation of flow pattern,

2. used to calculate the seepage flowrate,

3. used to calculate pore water pressure at any point on the cross-section, and

4. most importantly for the user to appreciate the possible groundwater flow and distribution of pore water pressure in the ground.

The flownet is constructed by trial and errors so as to satisfy the following conditions :

1. Flowlines cross equipotentials at right-angles.

2. Flowlines cannot cross other flowlines.

3. Equipotentials cannot cross other equipotentials.

4. Impermeable boundaries and lines of symmetry are flowlines : as there is no flow across them.

5. Bodies of water such as reservoirs are equipotentials.

6. The flownet must be constructed so that each element is a curvilinear square. - Although its sides may be curved, a curvilinear square is a broad and it is long, so that a circle may be inscribed within it.

Confined flownets — If all the boundaries to the flow regime are know at the outset, the flownet is described as confined.

Unconfined flownets — In case the soil surface does not remain flooded, the phreatic surface will be drawn down into the body of the aquifer. Practically, the phreatic surface represents the upper flow boundary or the top flowline. The position of the top flowline depends on the flow regime as represented by the flownet, while the flownet depends on the position of the top flowline. Unconfined flownets are more difficult to sketch than confined flownets. The position of the top flowline is located using the fact that the gauge pore water pressure at any point on it is zero. This means that the total head h at any point is equal to the elevation of that above the datum for measurement of h. For example, the 3 m equipotential intersects the top flowline at an elevation of 3 m above datum level. Using this additional condition, the top flowline or the phreatic surface may be correctly located by trial and error.

Boundary conditions for flow into drains

One of the purpose of slope drainage system is to ensure that the top flowline remains below the slope surface at all points. The sketching of flownet for any drainage system requires some understanding of the boundary conditions of different drains. This is also required for setting up appropriate models in numerical calculations. While a drainage blanket at the base of a fill slope can be assumed to be flooded, so that it acts as a reservoir or an equipotential, vertical toe drain for a slope will not be in general flooded (unless they are blocked), and so must treated differently. Assuming the drain is fully effective (will not trap water) and for coarse soils, the phreatic surface condition (pore water pressure = 0) is fulfilled at the interface between the soil and the drain. For fine grained soil, a small pressure difference between the pore water and the atmospheric air is required for the water to drain out of the soil - water exit effect.

Calculation of pore water pressure using the flownets

The pore water pressure at any point in a flownet may be calculated by interpolation between equipotentials. Therefore, we may be able to estimate the distribution of pore water pressure along potential slip surfaces and to assess the effectiveness of different drainage measures.

The first step is to calculate the total head (h) by linear interpolation between equipotential lines on the flownet. This must then convert to a pore pressure head (u / γ_w) by subtracting the elevation of the point A above the datum for the measurement of total head (h). The pore water pressure may then be calculated by multiplying the pore pressure head with γ_w.

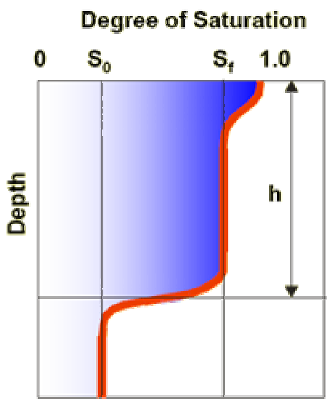
Infiltration into Unsaturated Ground

The ground above the phreatic surface is often unsaturated. The groundwater table may rise due to infiltration from the ground surface through the unsaturated soil into the aquifer. Many field measurements of groundwater levels are not sufficient for the stability analysis in slope design. The wetting band approach may be used to give a rough estimate of groundwater levels.

This approach takes no account of upslope infiltration and non-vertical flow within the slope. It assumes that the saturated (or near saturated) wetting band descends vertically under the influence of gravity, even after the cessation of rain, until it reaches the main water table. In this case, a sudden rise of the groundwater table for a height equals to the thickness of the wetting band occurs with a consequent increase in pore water pressure. If the wetting band reaches a zone of lower permeability, a perch watertable may develop above the zone of lower permeability.

$$h_{wf} = \frac{k\,t}{n(S_f - S_0)}$$

h_{wf} = depth of wetting front
k = saturated permeability of soil
n = porosity
S_0 = initial degree of saturation
S_f = final degree of saturation (= 1 for full saturation, smaller than but close to 1 in Lumb's experiments).
t = duration of rainfall/infiltration

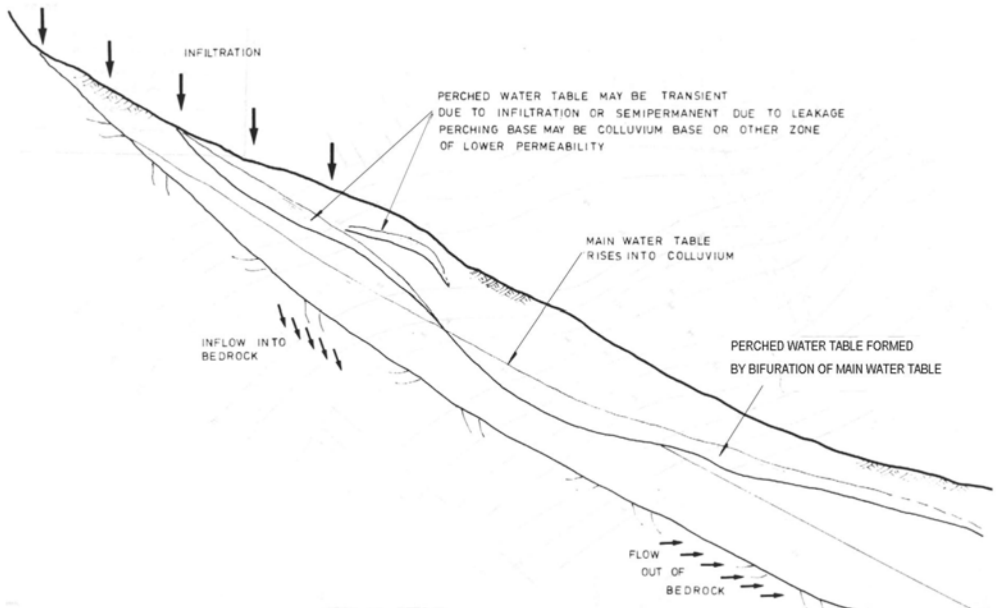


The intensity of surface infiltration is generally proportional to rainfall density but affected by the runoff characteristics of the ground. The wetting band thickness that forms as a result of rainfall is also related to the initial degree of saturation of the soil mass. Thicker wetting bands are therefore more likely to occur in wet season than after dry spells.

Infiltration is limited by the saturated permeability at surface or near surface strata. If the soil profile there exists a very thin band of material of permeability lower than the overlying and underlying materials, this will act as a throttle on infiltration. Above the wetting band, positive pore pressure will develop, while below the band full saturation is unlikely to achieve. Also, if the surface permeability is lower than that of the underlying material, the surface acts as a throttle and no band of saturation can develop.

Hillslope Hydrogeology – A conceptual Model

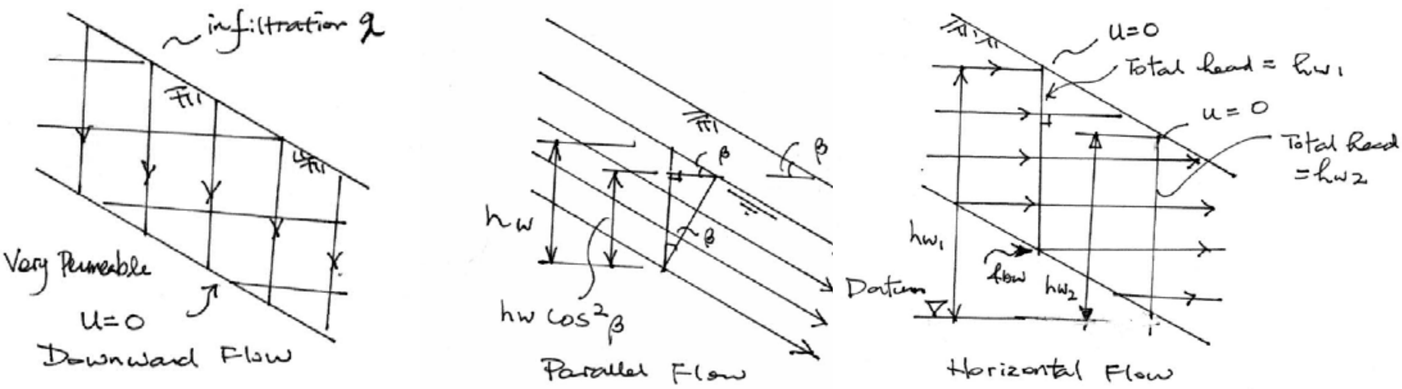
As part of the hydrogeological studies carried out by the GCO in the 1980's, a schematic hydrogeology of the hillside above Po Shan Road was established. Although the geological and hydrogeological conditions of each site are unique, we may make use this as our basic conceptual model for regional hydrogeology in hillslope areas of Hong Kong.



We can see from this diagram, permeability contrast in the ground give rise to a main inclined aquifer, together with areas of perched groundwater table. The main aquifer is the colluvium/residual soil. The 'bedrock' is relatively impermeable, however zones of high permeability within the top portion of the 'rockhead' due to concentrated groundwater flow, and due to fracturing of rocks close of faults or dykes. This 'bedrock' can be leaky and it may generate inflows into the superficial aquifer. The source of water flow in this system is mainly from surface infiltration. However, the groundwater condition can be affected by inflow into the 'bedrock' and outflow from the 'bedrock', especially at the foothill areas.

Microscopically, we can conceptually treat different portions of the hillslope hydrogeological system into three conditions:

Areas of downward flow occur when infiltration ≤ basal drainage. In this case, no pore pressure builds up and the movement of flow is driven by gravitation effect.



Areas of parallel downward flow are where inflow from the uphill area = outflow to the downhill area – no surface infiltration and no leakage from the base. We may make use of the concept of flowlines and equipotentials from flownet analysis to appreciate distribution of pore water pressure in the hillside.

In areas where there is inflow from the basal area, e.g. the presence of a vary permeable 'rock head' hydraulically connected to a uphill source, giving rise to horizontal flow condition. Under this condition, water will flow out from slope surface and the pore water pressure distribution in a slope is the same as that of a 'standing' groundwater table of a level ground.

Principal Sources/References

Gray, I. (1986). *The Design of Horizontal Drains to Improve the Stability of an Undeveloped Hillside*. Design Study Report No. DSR 3/86, Geotechnical Control Office, Hong Kong.
Powrie, W. (1997). *Soil Mechanics Concepts and Applications*. E & FN Spon.
Sun, H.W., Wong, H.N. & Ho., K.K.S. (1998). Analysis of infiltration in unsaturated ground. *Slope Engineering in Hong Kong*, A.A. Balkema, pp. 101-109.